WG3 Biorefinery Applications

CA 20127

Waste biorefinery technologies for accelerating sustainable energy processes (WIRE)

Deliverable D3.3 – Report on Research Gaps and Key Areas with High Potential for Academia and Industry Collaboration

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Funded by the European Union

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List of acronyms

AD	Anaerobic digestion
HTL	Hydrothermal liquefaction
GHG	Greenhouse gas
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing
MCA	Multi-Criteria Assessment
MCI	material circularity index
PHA	polyhydroxyalkanoates
SC	Struvite crystallization
S-LCA	Social Life-Cycle Assessment
TEA	Techno-Economic Analysis
TRL	Technology Readiness Level

INTRODUCTION

The development of biorefineries is essential for advancing a sustainable bioeconomy through the production of biofuels, bioproducts, and biomaterials from renewable resources. However, several scientific and technological challenges remain across the value chain.

Biomass supply is limited by seasonal availability, heterogeneity, and logistical complexity, requiring improvements in sustainable cultivation, supply chain management, and pretreatment processes. Genetic optimization of energy crops is also crucial to enhance compatibility with conversion technologies.

On the process side, the efficient deconstruction of lignocellulosic biomass remains a major bottleneck, with enzyme instability and inhibitory byproducts reducing conversion efficiency.

The integration of biochemical and thermochemical pathways, such as fermentation, pyrolysis, and gasification, offers potential for full feedstock utilization but remains technically immature. Similarly, upgrading intermediates like bio-oil, biogas, or syngas into marketable products is still in the pilot phase and demands further research.

The valorization of side streams, particularly lignin, could unlock new value chains for biobased materials and platform chemicals. Yet, these innovations face not only technical challenges but also regulatory and standardization barriers. In addition, the scale-up of biorefinery concepts is hindered by the lack of demonstration facilities and the complexity of integrating flexible, multi-step processes under real-world conditions. Sustainability assessments are often fragmented, with environmental and economic evaluations rarely linked to social impacts or public acceptance. This contributes to systemic uncertainty, complicating investment decisions and long-term planning.

To overcome these barriers, research should focus on optimizing biomass logistics, improving conversion efficiency, advancing system integration and scale-up, and conducting comprehensive sustainability assessments. Strong collaboration between academia and industry, especially in pilot plant development, technology integration, and socio-economic research, is key to translating biorefinery innovations into viable, large-scale applications.

Hence, government policies and incentives (e.g., tax credits, grants, and subsidies) should be provided to balance the capital and operational costs associated with biorefinery investments. Moreover, awareness should also be built by educating consumers, end-users, and industries that will benefit from bio-based products. In this context, potential environmental benefits (e.g., greenhouse gas mitigation, reduced water usage, and improved nutrient management) of biorefineries should be explained in comparison with fossil-intensive production (Makepa and Chihobo, 2024).

This report analyzes research gaps and identifies key areas with high potential for collaboration between academia and industry in the field of applications of biorefinery-derived products. The aim is to provide a critical overview of underdeveloped and emerging sectors, guiding future joint research and investment activities.

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<tr><td>Limitations in catalysts, process selectivity, thermal integration, Issues related to process scaling or efficiency.</td><td>Are there microbial strains or enzymes that remain underexplored? Lack of standardized methods for industrial genetic engineering.</td><td>Immature enabling technologies (e.g., continuous processing, advanced sensor systems), Need for digitalization, AI, advanced process modelling</td><td>Difficulties in full life cycle assessments (LCA, carbon footprint), Gaps in real environmental impact monitoring</td><td>What regulatory barriers limit scalability?, Lack of incentives or viable business models?</td></tr>
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Table 1: Scheme proposed for the identification of research Gaps for Academia and Industry collaboration.

In the context of the COST Action WIRE, this report includes literature data and research experience from WIRE participants within the WG3 – Biorefinery applications.

Cross-cutting examples are provided from biochemical, thermochemical, and chemical processes. Specifically, the report discusses the lack of information and connection between various products and the corresponding conversion routes from the academia and the real scale applications, with a particular focus on: biogas obtained via AD and its uses, the process for bioethanol production, biocrude from HTL, SC for nutrients recovery, and biofuels in general and case study in Germany, and the company 3R-BioPhosphate example. Additionally, the report includes brief notes on the emerging topic of plastic recycling and monomer reuse. Based on discussions and exchanges among WIRE and WG3 participants, during both online and in-person meetings, a matrix (see Table 1) was created to identify, for each process/product within the biorefinery context, the information needed to fill the existing gaps.

1. Bioethanol research Gap

As a sustainable alternative to conventional fossil fuels, bioethanol can reduce dependence on petroleum products and operate effectively in internal combustion engines (Barua et al., 2023; Kazmi et al., 2025). The production and use of biofuels have been found to perform better than conventional fuels in terms of environmental impact, particularly by reducing GHG emissions, such as CO_2 (Mvelase et al., 2023; Kazmi et al., 2025). Furthermore, bioethanol derived from waste materials, such as food waste, offers a sustainable approach to meet energy needs while also addressing the growing problem of waste disposal (Kazmi et al., 2025). Bioethanol production is typically classified into four generations, each defined by the feedstock used (Jain and Kumar, 2024; Kazmi et al., 2025; Yaverino-Gutiérrez et al., 2024). First-generation (1G) bioethanol is derived from food crops like sugar cane and corn, which have a higher feedstock cost but a lower processing cost. However, this method raises concerns about food scarcity (Jain and Kumar, 2024). Second-generation (2G) bioethanol utilizes abundant and low-cost lignocellulosic biomass, such as agricultural waste and wood residues, making it a more widely adoptable option (Jain and Kumar, 2024). The third-generation (3G) primarily uses algae, while the fourth-generation (4G) involves genetically modified algae to improve yields (Jain and Kumar, 2024).

The primary technological gap in the bioethanol field is the economic viability of 2G bioethanol derived from lignocellulosic biomass (Jain and Kumar, 2024). Despite significant technological development, the high cost of processing, particularly during the pretreatment stage, makes 2G bioethanol uncompetitive with gasoline (Jain and Kumar, 2024).

Additionally, there are challenges in optimizing the production process itself. These include:

- Strain Selection and Optimization: There is a need for further research to identify and optimize microorganisms for on-site cellulase production to enhance productivity and feasibility (Afedzi et al., 2025).
- Early Development of Advanced Generations: While 3G and 4G biofuels from algae hold promise, they are still in their early research and development stages, with microalgae production being particularly expensive (Jain and Kumar, 2024; Kazmi et al., 2025).
- Downstream Processing: Challenges remain in optimizing downstream processes to efficiently recover ethanol (Afedzi et al., 2025).

Joint efforts are most urgently needed in the following areas to bridge the gap between research and commercial application:

- Cost-Effective Pretreatment and Hydrolysis: Academia and industry must collaborate to develop cheaper, more efficient, and integrated pretreatment methods for lignocellulosic biomass (Yaverino-Gutiérrez et al., 2024). Research should focus on synergistic hybrid methods to enhance efficiency (Jain and Kumar, 2024).
- Process Optimization and Innovative Technologies: Collaborative research is vital for advancing technologies like cell and enzyme immobilization to improve stability, reusability, and overall process efficiency (Afedzi et al., 2025; Chacón-Navarrete et al., 2021). Academia can provide a scientific basis, while industry can focus on scaling and implementing these methods cost-effectively.
- Valorization of By-products: Developing zero-waste biorefinery models is a critical area for collaboration (Barua et al., 2023; Osmolak et al., 2025). By simultaneously producing bioethanol and value-added co-products from waste materials, the overall economic viability of the process can be significantly enhanced (Osmolak et al., 2025).

Several barriers impede effective collaboration between academia and industry:

- High Production Costs: The most significant barrier is the high production cost of lignocellulosic bioethanol, which makes it less competitive than fossil fuels (Jain and Kumar, 2024). Without a clear path to economic feasibility, industrial investment is limited (Mizik, 2021).
- Lack of Supportive Policy and Regulatory Frameworks: The successful commercialization of bioethanol requires supportive policies and incentives that can de-risk industrial investments and facilitate the scale-up of new technologies (Afedzi et al., 2025).
- Social and Environmental Concerns: Public perception and concerns surrounding land use changes for feedstock crops and the potential for food scarcity present non-technical barriers that require social and political dialogue (Mvelase et al., 2023). For advanced generations, there are also concerns about the release of genetically modified algal strains into the environment (Kazmi et al., 2025).
- Incompatible Approaches: Academia often focuses on fundamental research, while industry requires scalable, commercially viable solutions. Bridging this gap requires joint projects and knowledge transfer initiatives that align both basic and applied research goals (Afedzi et al.,

2025). Additionally, as in many other industries, companies often prefer to conduct in-house R&D to retain full control over intellectual property and avoid sharing commercialization rights.

Finally, some microbial strains or enzymes remain underexplored, and there is also a corresponding lack of standardized methods for industrial genetic engineering. For instance:

- Microbial Strain and Enzyme Exploration: Focus on developing robust, high-yield microorganisms through genetic engineering that can tolerate harsh conditions, such as the inhibitors present in lignocellulosic hydrolysates (Yaverino-Gutiérrez et al., 2024). This also includes further exploration of underexplored microbial strains and enzymes.
- Immobilization Technologies: Further exploration of low-cost, natural materials as carriers for yeast and enzyme immobilization to enhance fermentation performance and reusability, a key area for improving the economics of 2G bioethanol (Chacón-Navarrete et al., 2021; Ogawa et al., 2024).

All these points must also be accompanied by an assessment of LCA. Conduct joint LCAs to quantify the environmental benefits of bioethanol, particularly in terms of greenhouse gas emission reductions, and to identify and mitigate potential negative impacts (Kazmi et al., 2025). In addition, fundamental is the waste Valorization. Develop sustainable and integrated biorefinery concepts that utilize waste streams and by-products to achieve a circular bioeconomy and reduce overall environmental footprint (Osmolak et al., 2025).

Academia should collaborate with industry to perform comprehensive TEA to identify bottlenecks and guide research towards economically viable solutions (Jain and Kumar, 2024). Jointly advocate for policies that support the bioeconomy, such as carbon pricing mechanisms, tax incentives for biofuel production, and mandates for biofuel use (Afedzi et al., 2025).

2. Biogas from AD

Although biomass has huge potential as an energy source, its utilization faces certain limitations, e.g., the seasonality and geographic variability of supply for many feedstocks, relatively low energy density compared to fossil fuels, as well as constraints associated with large-scale cultivation of feedstock on agricultural lands. Despite significant technological progress over the past decade, the commercial implementation of producing multiple fuels, chemicals, and materials from sustainable biomass feedstocks remains limited.

These limitations also apply to biogas production plants, such as AD plants for different types of biomass as manure, sludge, or animal residues.

Before constructing a biogas plant, the risks involved in each step should be evaluated.

There are two possibilities for an investor during biogas plant planning:

- the first one is to supply materials to an existing or newly constructed biogas plant,
- the second possibility is to work with a private biogas plant and share the generated electricity from biogas before selling it to the market.

In the first one, there is a low risk in terms of investment, but low utilization of the value produced from biogas, while in the second one, there is a high risk in terms of investment and biogas plant operation, but high utilization of the value produced from biogas. On the other hand, there are several legal barriers that arise for a plant operator during both the planning and operation of the biogas plant. Even before the plant is built, the operator must consider the grid connection, the drafting of the contract, and the requirements related to the laws. During the conceptual design period, the plant design, the selection of materials and technologies used, and various possibilities for energy utilization should be evaluated, taking into account the allowance rates and incentives from the Renewable Energies Law. Consequently, the plant operator must comply with all relevant requirements during the operation of the plant, operate the plant in compliance with the Renewable Energies Law criteria, and meet all legal obligations. For example, to receive the incentive according to the Renewable Energies Law, the biogas plant operator must himself find a solution to feed the electricity generated to the general electricity grid. Besides, biogas plants are highly dependent on the production of market crops. Corn silage production, for example, has a 30-40% dry solids ratio in the raw material and the ability to store the ensiled material for a maximum of 24 hours after removal from storage. This means that it has only limited transportability after removal from storage. Thus, if the biogas plant manager has his own silo, a regional market can be considered.

In order to get the licensing of a biogas facility, the legal requirements (e.g. building planning and building regulations, regulations related to air, surface water, and environmental protection, as well as solid waste, fertilizer, hygiene regulations, and environmental compliance control regulations) must be fulfilled. Furthermore, if animal by-products, including farm manure of animal origin, are used in a biomass facility, provisions regarding animal disease outbreak regulations may also be taken into account. Accordingly, during the licensing process, the need for expert assistance in applying for a license is also highlighted in the related regulations. Since licensing practices vary across states, the operators should contact local authorities promptly for licensing.

Depending on the materials to be used in the plant, the operator must meet the criteria of the related directives. Changes in gas yield, methane content, electricity yield, and material costs, especially in plants with a high renewable waste content, have the greatest impact. Similarly, a change of 1 ct/kWh in the electricity sales price would have a significant impact.

Besides, the silage capacity for direct sale from the field should be provided on the site (next to the biogas plant) due to the transportation requirement and its cost. Besides, biogas plant operators strive to secure long-term contracts to ensure a relatively constant supply of material. However, fulfilling contract terms can be challenging for farmers, especially when the expected yields are not met.

Therefore, the production and use of biogas, particularly in rural areas of as in Turkiye, can support economic and social development. In addition to gasification for electricity generation, there are also plants that use the direct combustion of waste biomass. According to Turkish Electricity Transmission Corporation data, the installed capacity of biogas, biomass, waste heat, and pyrolytic oil power plants was 1,163 MW by the end of 2019, generating 4,524 GWh of electricity. There are about 110 biogas plants in about 32 cities of Turkey with a potential of ca. 370 MW of electricity. On the other hand, around 13 million tons of digestate production is estimated. It is considered that digestate usage is a critical bottleneck that will limit the future expansion of the biogas industry.

Before the construction of a biogas plant, the following issues should be primarily taken into account:

- The operating income against risks should be protected (based on the existing price guarantee for electricity produced from biogas) throughout the year;
- Agricultural lands should be evaluated independently of the agricultural market.
- Primary and by-products should be utilized for energy production.
- Emissions and odors from the storage and field application of farm manure should be monitored and reduced.
- The availability of nutrients in farm manure to plants should be improved.

3. Research Gaps and Innovation Potentials in Biofuels and Biorefineries in Germany and Saxony

Germany reflects international research gaps and innovation potentials in the field of biofuels and biorefineries, while demonstrating distinct national strengths. Key challenges include the efficient use of heterogeneous biomass such as straw, green waste, and wood residues. Current research emphasizes decentralized, modular pretreatment units and logistics to ensure sustainable and cost-effective feedstock supply. Technological integration is driven by pilot facilities at institutes like ATB and DBFZ, focusing on smart process control, AI, digital twins, and advanced sensors for flexible biomass processing. Novel reactor concepts and lignocellulose fractionation are under investigation. Sustainability is a cornerstone of German biofuel policy, with stringent certification ensuring over 90% greenhouse gas savings. However, calls persist to extend these standards to all biomass products and to systematically assess social impacts and public acceptance, particularly in the context of the "food vs. fuel" debate.

Germany promotes system-oriented approaches through demonstration plants and innovation hubs, integrating technical, social, and economic dimensions, and strong collaboration across science, industry, policy, and agriculture supports scalable, resilient bioeconomy infrastructures.

Key collaboration potentials lie in open-innovation platforms, efficient interface management along biomass value chains, and robust knowledge transfer through institutional networks. Germany thus positions itself as a European leader in sustainable and digitally enabled biorefinery development, although further progress is needed in complete biomass utilization, digital integration, system-level sustainability assessment, and economic scalability.

Scaling up biorefinery technologies from lab or pilot scale to industrial application involves complex technical, economic, and regulatory challenges. High capital investment and perceived financial risk hinder commercial deployment, prompting the need for public-private partnerships and flagship demonstration projects.

Industrial operations must flexibly handle variable, seasonal biomass feedstocks, requiring efficient logistics and decentralized preprocessing. The complexity of integrating multiple biological and chemical processes, combined with fluctuating inputs and outputs, demands robust control systems and advanced quality management. While Germany is advancing digital tools such as AI and digital twins, their large-scale implementation remains limited. Additionally, strict but sometimes ambiguous regulatory and certification frameworks can delay industrial realization.

Long-term demonstration projects, multi-stakeholder cooperation, and adaptive policy frameworks are essential to ensure technical robustness, economic viability, and sustainable market integration.

The key unresolved challenges span both engineering and environmental sciences. Continuous processing technologies, such as continuous fermentation and reactive extraction, remain underdeveloped at an industrial scale due to process complexity, sensitivity to feedstock variability, and a lack of scalable, robust reactor designs. Most implementations are limited to lab or pilot scale, with significant gaps in achieving stable, economically viable continuous production. Similarly, the integration of advanced sensor systems for real-time monitoring of process parameters, side streams, and material flows is still in its infancy. The adoption of Industry 4.0 technologies, including digital twins, smart control systems, and predictive maintenance, face practical limitations, especially where biological and chemical-physical steps must be tightly coupled.

In parallel, AI-driven process modeling and optimization are hindered by a lack of operational, high-quality datasets. Existing models are often theoretical or focus on isolated process steps, while integrated multi-scale models that bridge biology, chemistry, and engineering are largely absent.

On the environmental side, conducting comprehensive and comparable LCA remains difficult due to heterogeneous process chains and incomplete data on emissions, energy consumption, and side-product utilization. Furthermore, real-time and long-term monitoring of environmental impacts, such as effects on biodiversity, soil, and water use, beyond standard LCA frameworks, is rare, limiting systemic evaluation and circular economy implementation.

Saxony case:

Saxony's energy transition strategy stresses the importance of biomass alongside wind and solar as a flexible renewable resource. Biomass already represents the largest renewable primary energy carrier in the region, with over 300 biogas plants in operation and significant employment in the sector. However, conventional energy crops such as maize face ecological and social acceptance challenges.

Novel substrates such as perennial Silphium, invasive species, and agricultural wastes offer both ecological benefits and energy potential. Invasive plant removal, while not cultivated, provides a biomass stream that can be converted into energy rather than wasted. This project complements this perspective by experimentally quantifying methan yields of invasive plants and wastes, while comparing AD and IFBB pathways through LCA (Angelidaki & Sanders, 2004; Muñoz et al., 2014). The combined approach aligns with ISO-based LCA methodology (ISO, 2006) and IPCC climate reporting standards (IPCC, 2013). Thus, this deliverable integrates policy, experimental, and LCA insights to identify research gaps (D3.3).

- *Science and technology gaps*

Methane leakage in AD systems is a dominant GHG source and requires technological solutions (Herrmann et al., 2016). High thermal energy demand in IFBB nearly doubles that of AD, limiting efficiency despite higher fossil substitution (Muñoz et al., 2014). Feedstock heterogeneity: blends of agricultural residues and invasive plants often show reduced yields due to nutrient imbalances (Nwanegbo, E., et al., 2025). Limited pilot-scale data for IFBB in Saxony restricts large-scale feasibility analysis. Standardization gaps in batch methane yield testing prolong experimental times and complicate cross-study comparison (Angelidaki & Sanders, 2004).

- Joint Research Priorities

Process optimization using digital tools (GIS, AspenPlus simulations) to model substrate potentials and optimize fermentation. Hybrid systems integrating AD and IFBB to balance methane leakage with fóssil substitution benefits.

- Performing various type of biomass pretreatment to increase biogas production.

Nutrient recycling and soil health integration via digestate application and biodiversity-supporting perennial crops. Ecosystem services from invasive biomass removal, linking biodiversity protection with energy recovery.

- Barriers to Collaboration

Technical: insufficient long-term operational data for non-traditional substrates.

Economic: high investment costs for IFBB retrofits and limited incentives forcdecentralized upgrading.

Regulatory: unclear classification of invasive biomass and manure co-digestion in EU waste regulations.

Knowledge transfer: fragmented networks between universities, regional businesses, and municipal stakeholders.

4. Hydrothermal liquefaction process for biocrude production

HTL has emerged as one of the most promising conversion pathways for wet biomass and organic residues within the biorefinery concept. HTL typically yields four product streams—biocrude, an aqueous phase rich in organics and nutrients, a small gas stream (CO_2-rich), and char/mineral solids, whose relative distributions depend on feedstock and conditions.

Beyond the bench scale, the field has progressed toward continuous-flow reactors and integrated upgrading, which are essential for techno-economic viability. Continuous HTL brings several challenges, including distinct hydrodynamic, heat-transfer, and solids-handling, but it enables steady operation, heat recovery, and coupling to hydroprocessing (hydrodeoxygenation/denitrogenation) to produce refinery-compatible fuels (diesel/naphtha/jet).

Critical reviews of continuous HTL highlight materials selection, plugging/coking control, and phase-separation design as pivotal, while emphasizing the need for robust, long-duration datasets (Castello et al., 2018). Managing and valorizing the aqueous product phase remains a strategic lever: it contains small organics, ammonia, and nutrients that can be recycled to algae cultivation (e.g., through the formation of NaHCO3) or treated via AD or catalytic hydrothermal gasification to enhance overall carbon and nutrient utilization.

Solar-assisted HTL couples the endothermic heat requirements of HTL to concentrated solar technologies (CST) or solar-thermal fields, aiming to offset fossil energy inputs, reduce operating costs, and improve cradle-to-gate greenhouse gas performance, allowing even for off-grid operation of such systems (Tsongidis et al., 2020; Poravou et al., 2023). Early techno-economic analyses explored parabolic-trough or solar-tower configurations to supply process heat or preheat streams, finding that solar integration can lower the levelised costs when paired with nutrient recycling and appropriately sized thermal storage (Pearce et al., 2016). Conceptual designs for CST-powered microalgal biorefineries have been mapped with plausible plant layouts and integration points, and the sensitivity of economics to solar resource, storage, and hydrotreating hydrogen sources has been quantified (Giaconia et al.).

However, significant scientific and technological gaps still prevent the industrial maturity of HTL to produce a biocrude that could be upgraded into biofuel, biodiesel, or sustainable aviation fuel (SAF).

A key challenge is the lack of harmonized methodologies and datasets across the field, with variations in feedstock preparation, reactor design, heating profiles, and analytical protocols leading to large discrepancies in reported yields, product quality, and mass balances. This inconsistency makes it difficult to compare results, generate reliable predictive models, or perform robust techno-economic and life-cycle assessments, which are critical for scaling the technology to industrial applications (Toor et al., 2011; Gollakota et al., 2018). Furthermore, while most academic research has been conducted in batch reactors, industrial deployment requires continuous HTL systems. Continuous operation poses major difficulties and challenges, including reliable pumping of biomass slurries under subcritical conditions, solids handling, and long-duration reactor stability against corrosion, plugging, and fouling. Although continuous prototypes exist, long-term performance data and validated process designs remain scarce, slowing down industrial confidence and investment (Castello et al., 2018; Elliott et al., 2015).

Another major challenge is the upgrading of HTL biocrude. The crude oil typically contains high levels of oxygen, nitrogen, sulfur, and metals, rendering it unstable and incompatible with existing refining infrastructure. Current upgrading strategies rely heavily on hydrogen-intensive hydrotreating and catalysts that are highly sensitive to impurities, yet there is still a lack of shared protocols and large-scale validation studies to standardize catalyst testing and define contaminant tolerance (Eliott et al., 2015). At the same time, the aqueous phase generated during HTL, which is rich in organics and nutrients, remains underutilized. Valorization options such as AD, catalytic hydrothermal gasification, or nutrient recovery have been proposed, but their integration into a cost-effective and sustainable HTL process is still not entirely understood (Watson et al., 2020). Last but not least, feedstock heterogeneity represents an overarching challenge, as predictive models are not yet capable of linking compositional variability to reliable yield and quality outcomes, limiting the ability to design robust and flexible feedstock supply chains for industrial-scale HTL and its integration into the biorefinery concept.

In the case of solar-assisted HTL, additional knowledge gaps exist that are specific to the integration of CST with HTL processes. Although solar heat has the potential to significantly reduce fossil energy demand and improve the sustainability profile of HTL, integration strategies remain largely at the conceptual or lab-scale level.

Technical barriers include thermal energy storage requirements, reactor and materials compatibility at high and fluctuating temperatures, and process control under intermittent solar input (Pearce et al., 2016; Giaconia et al, 2017). Very few pilot-scale demonstrations have progressed so far, meaning that the techno-economic and environmental benefits of solar-assisted HTL remain largely theoretical. Moreover, the field as a whole suffers from a data and digitalization gap: the lack of large, harmonized, and openly accessible datasets prevents the application of machine learning, process simulation, and digital twin.

HTL and solar-assisted HTL present multiple opportunities for effective collaboration between academia and industry, particularly in bridging gaps between fundamental research and commercial-scale deployment.

- One priority area is the development of continuous-flow HTL systems as mentioned above, where academia can investigate reaction kinetics, slurry rheology, and fouling mechanisms, while industry contributes expertise in reactor engineering, materials selection, and long-term operational reliability.
- Upgrading of HTL Biocrude also offers collaboration potential, with universities and RTOs developing novel catalysts and refining methods, and industrial partners providing realistic co-processing environments to test scalability and contaminant tolerance. Valorization of the aqueous phase represents another fertile ground for partnership, combining academic research on catalytic and biological conversion with industrial experience in wastewater or agricultural operations. For solar-assisted HTL, joint projects could explore thermal integration, energy storage, and process control under fluctuating solar inputs (on-sun and off-sun operation due to several reasons), moving concepts from lab-scale to pilot-scale demonstrations.
- Finally, digitalization and machine learning offer strong synergy:
  Academia can develop predictive models, while industry can supply operational datasets enabling pre-competitive platforms for data sharing and digital twin development.

Data fragmentation and inconsistent reporting practices discourage the industry from relying on academic results, while academic incentives often prioritize publications over pre-competitive data sharing.

- Intellectual property rights (IPR) and commercial sensitivity create further hesitation, as companies are reluctant to disclose operational details that might compromise competitive advantage.
- Regulatory uncertainty, covering among other fields, biocrude classification, wastewater treatment permits, fuel standards, and co-processing rules, adds additional risk and slows pilot deployment.
- Funding structures also present obstacles, since public grants typically support fundamental research but not the capital-intensive pilot or demonstration facilities that are essential for bridging the gap to industrial adoption.

The lack of large-scale solar-assisted projects apart from electricity generation also plays a major role in the advancement of the technology.
Addressing these barriers through pre-competitive consortia, blended funding mechanisms, and regulatory engagement will be critical for accelerating the development and deployment of HTL-based biorefineries.

To overcome some of the issues, as HTL and solar-assisted HTL are fundamentally chemical conversion processes, chemical and process engineering research is critical.

- Key suggestions include the development of advanced catalysts for upgrading HTL biocrudes that can tolerate high oxygen, nitrogen, sulfur, and metal contents. Research should focus on improving process selectivity, minimizing unwanted side products, and increasing biocrude yields. Thermal integration studies are essential, especially for solar-assisted HTL, to optimize heat transfer from concentrated solar thermal (CST) systems and reduce fossil energy inputs.
- Immature enabling technologies: engineering and automation represent critical areas where research and collaboration are essential due to the immaturity of enabling technologies. As already described, continuous-flow operation remains challenging, particularly in handling heterogeneous biomass slurries at high pressure and temperature, managing solids, and preventing fouling and corrosion over long durations. Advanced sensor systems and process monitoring technologies are underdeveloped, limiting real-time control and predictive maintenance. There is a strong need for digitalization and AI-based process modeling, including machine learning approaches and digital twins, to optimize reactor performance, predict yield and quality variations, and guide control strategies under variable feedstock and solar conditions.
- Regulatory uncertainty around biocrude classification, wastewater discharge, fuel standards, and co-processing in existing refineries limits investment and pilot deployment. The lack of clear incentives, subsidies, or feed-in tariffs for renewable energy biofuels reduces the attractiveness of HTL-based biorefineries for private investors. Furthermore, viable business models are still underdeveloped, as the techno-economic. The feasibility of integrating HTL into existing industrial or municipal infrastructure depends on local feedstock availability, market demand for biofuels, and the valorization of by-products such as the aqueous phase and solid residues.

5. Struvite crystallization (SC) from wastewater for nutrient recovery

Within the framework of biorefinery and process integration, the valorization of by-products from ancillary processes should also be considered, as these can find applications in other sectors — for instance, the use of struvite for nutrient recovery.

SC from wastewater is one of the most promising sustainable routes to alleviate phosphorus supply problems and mitigate environmental degradation caused by inadequate waste treatment. This process enables nutrient recovery from waste, currently disposed of in the environment. During SC, magnesium (Mg2+), ammonium (NH4+), and phosphate (PO43-) can be recovered in equal molar concentrations from wastewater, and mostly from the liquid fraction of the digestates, as struvite (MgNH4PO4·6H2O) fertilizer. Struvite is a crystalline mineral, with structures such as orthorhombic, and is a slow-release fertilizer that can replace industrial phosphate fertilizers, currently mainly manufactured from the depleting phosphate rock.

Litterature and data from research of WIRE participants focus on SC (Yan and Kallikazarou et al., 2025) from livestock wastewater through bench-scale and pilot-scale studies. Pilot-scale SC experiments were conducted in a 250-L SC reactor (SCR) at CUT, using different matrices and magnesium sources. Struvite precipitates formed using magnesium hydroxide, and both matrices met regulatory fertilizer standards (Kallikazarou et al., 2025a).

In a separate study, fed-batch feeding during AD was investigated for its influence on struvite quality. Intermittent feeding helps prevent free ammonia nitrogen toxicity and volatile fatty acid (VFA) accumulation, which are common issues when processing livestock waste (Yan and Kallikazarou et al., 2023). In this way, effluent quality can be improved, and organic matter can be removed, thus enhancing digestion efficiency and struvite quality (Angelidaki et al., 2011; Fotidis et al., 2014; Tian et al., 2017).

AD was performed under mesophilic conditions (37 ± 1 °C) in the 10-ton reactor of the CUT pilot. The gradual feeding to the SCR over a period of 23 days produced 52.40 m^3 of methane, achieving 89.7% of the theoretical methane yield.

Biogas had approximately 60% v/v CH_4, within the typical range of 50–70% v/v. The final struvite precipitate met the regulatory requirements for solid organo-mineral fertilizers (Regulation EU 1009/2019) (Yan and Kallikazarou et al., 2023).

Through an integrated treatment approach, the application of a fed-batch feeding strategy during AD resulted in the simultaneous production of both biogas and struvite fertilizer.

Despite significant advances in AD and SC, their broader industrial uptake is limited by key gaps that require urgent joint academia–industry efforts. Scaling beyond municipal wastewater to diverse streams such as ship waste demands tailored pretreatment strategies, pilot-scale demonstrations, and integration of AD with digestate dewatering and SC.

Addressing process inefficiencies remains critical: specific pretreatments, strategies for inhibition control, as well as energy- and reagent-efficient crystallization methods are needed to improve economic feasibility.

At the same time, research must focus on optimizing product quality through purification, granulation, and co-production of high-value bioproducts, ensuring both agronomic performance and market acceptance.

Equally urgent are regulatory and economic challenges, where academia can provide risk assessments, LCAs, and harmonized quality benchmarks, while industry can supply real-world operational data. Demonstration of advanced digestion configurations, integration with renewable H_2, and the development of circular business models will be crucial to bridging the gap from lab-scale innovation to scalable, standardized, and commercially viable nutrient recovery systems.

Current barriers to collaboration between academia and industry in the biorefinery field stem largely from misaligned priorities and limited mechanisms for knowledge transfer. Academic research often emphasizes innovation, mechanistic understanding, and publication, whereas industry prioritizes cost-efficiency, regulatory compliance, and rapid deployment. This misalignment can slow the translation of promising lab-scale advances, such as novel pretreatments or electrochemical precipitation, into pilot and commercial applications. Furthermore, data sharing remains limited, as companies ma be reluctant to disclose operational information due to competition or intellectual property concerns, while academic projects may lack access to diverse real-world wastewater streams. Additional barriers include fragmented regulatory frameworks, which create uncertainty around the marketability of recovered products like struvite fertilizers, discouraging industrial investment. Finally, financing gaps still persist. Overcoming these barriers requires stronger alignment between research objectives and industrial needs.

SC and AD enable sustainable nutrient recovery and biogas production, but industrial uptake is limited by technical gaps such as scaling, tailored pretreatments, inhibitor control, and energy efficiency. Product quality, post- processing, and co-production of valuable bioproducts are key for market uptake. Regulatory gaps, unclear standards, and weak incentives also limit commercialization.

6. Biobased monomers derived from renewable resources

Biopolymers, but also biobased monomers derived from renewable resources and extractable in waste biorefineries, are promising candidates for the substitution of synthetic polymers that originate from fossil fuel resources. According to the EU Biorefinery Outlook project (2021), the materials product group of a biorefinery contains composites, fibers, polymers, and resins. More specifically, a biorefinery can produce pulp and paper, cellulose and cellulose derivatives, lignin, tall oil, starches, pyrolysis oils, biochar, and resins. In the literature, there are two general categories of biorefineries defined. The bottom-up approach, which extends or upgrades already existing conventional biomass processing facilities characterized by a TRL of 9 (commercial scale), such as sugar, starch, or pulp mills. The second approach is the so-called top-down approach, where new value chains are developed using highly integrated processing systems. Today, with the exception of traditional raw materials like fibers from agricultural and forest products industries, such as cellulose and its derivatives, only a small number of bio-based building blocks have been successfully developed into industrial materials (Tardy et al, 2022). As one outstanding example, the YXY® plants-to-plastics Technology of the Dutch company Avantium, which transforms fructose into furan dicarboxylic acid (FDCA), the monomeric building block for polyethylene furanoate (PEF). PEF production was scaled up to pilot scale already in 2011, and the pilot plant was run 24/7 all year round in order to demonstrate scalability and produce the necessary amounts of FDCA and PEF for applications development with partners (de Jong et al 2022). Besides renewability, the biodegradability of biopolymers is a key point for certain applications in order to reduce non-recyclable waste streams. Certainly, biodegradability must not come at the cost of the performance of the materials that should be substituted, which in many cases are high-performing in stringent conditions regarding their mechanical, thermal, and dimensional stability. This competitive balance between performance and cost will be established only if translation of fundamental research is accelerated and if applied research and industry clearly identify how to overcome the bottlenecks for the implementation of biobased substrates into materials production (Tardy et al, 2022).

The primary limitations for the implementation of bio-based building blocks are low homogeneity, variability in their performance from batch to batch, the scale that is available, like the minimum amount to run a pilot plant, or the yearly availability of the supply chain, still missing life cycle and feasibility studies, policies and regulatory issues, and still unknown environmental impacts of a long-term mass production. The heterogeneity of natural biopolymers stems from their inherent natural biosynthetic process, which is dependent on the species but also on the climate. Thus, the same biopolymer extracted from different sources, but also the biopolymer from the same species but from different seasons, will show differences in structure and purity (Tardy et al, 2022). Problems connected with resource availability can exist because waste materials need to be collected and sourced for an eventual appropriate utilization for biomaterials production due to an unestablished supply chain.

Bio-based materials can be of lower quality and lower performance compared to the fossil-based conventional products. Further, in order to achieve a competitive performance, the refining costs via downstreaming steps can increase too much. It can be difficult to show the performance of bio-based material products due to obstacles in scaling up production, and eventually difficult access to the market or due to low engagement of external partners in product development (Annevelink et al, 2022).

Scaling up while maintaining product quality and performance is a key element. Considering the need for bigger processing facilities, academia needs support from industry, especially in scaling up.

Demonstrating the performance and functionalities involving external partners, which are important players in the respective market, is a necessity to have a chance to enter new markets. Here, the active involvement of industrial players would be desirable. This could be achieved by the application for PhD programs with industry involvement, which is already a reality, for example, in Italy, where industrial partners can profit from a 100% refund of costs. However, funding is not always easily accessible.

One important area is standardization to obtain scientific results that are benchmarked and reproducible, so they can directly improve the practices used in industry. In the same way, the commercial solutions in use by industry need to be benchmarked, and their minimum requirements to achieve the requested performance of commercial products need to be disclosed and communicated in order to establish well-defined objectives for research questions in academia (Tardy et al, 2022).

Maybe the biggest barrier, especially for SMEs, is the availability of personnel who can be dedicated to the research questions. Again, this could be overcome by “industrial PhD programs” where PhD students figure as the employees of the industrial partner and can dedicate 100% of their time to the research question.

The different approach to reporting in academia and industry is considered an obstacle since the practices usually used in academia cannot be adopted by manufacturers, as they are used to different reporting standards. Further, timelines are considered much stricter in industry than in academia. Another obstacle for the development of a regular cooperation is the expectation for outcomes, which are generally process-centered in industry, while they are data- or concept-centered in academia (Tardy et al 2022).

7. 3R-BioPhosphate Ltd.: Upcycling engineer

3R-BioPhosphate Ltd provides core research and industrial expertise in zero-emission/energy independent processing and the circular economy-based reuse of unexploited biomass. The User, application and market-driven research work spans from technology and product development through applied research, all the way to full industrialization and commercialization, effectively translating science into market-driven industrial practice.

The 3R is an industrial technology and commercial product developer of recovered bio-based products for biofertilizer and adsorbent applications. Research and industrial design specialized in the integrated industrial processing and valorization of agri/food by-product streams using innovative high-temperature pyrolysis and biotechnological methods. We specialize in the upcycling of economically high nutrient density, food-grade animal bones into economical 35% P2O5 high nutrient density bone char using the proprietary 3R zero-emission pyrolysis technology and its tailored formulations. This process enables the recovery and upcycling of BioPhosphate, a critical raw material sourced from food-grade animal bones. Phosphorus is recognized as a critical raw material with high supply risk and significant economic importance, making reliable and uninterrupted access a key concern for European industry and value chains.

The research objectives include the industrial-scale production of all biochar types, as well as high-nutrient-density recovered phosphorus products, nutrient recovery, and BIO-NPK-C fertilizer formulations.

The 3R is also specialized in EU policy and regulatory harmonization for the Circular Economy, and a REACH expert for chemically modified substances, with a focus on ABC Animal Bone Char, Animal Bone Oil, and biochar products. The research works also include authority permitting procedures for full industrial-scale implementation of innovative recovery technologies, including environmental impact assessment, process safety, and energy efficiency evaluation.

– Industry Perspective on Research Gaps and Collaboration Opportunities in Biorefinery Applications

As a company operating in the field of advanced biorefinery solutions, 3R-BioPhosphate Ltd recognizes several critical gaps and challenges that hinder the effective transition of scientific innovation into market-ready technologies. In particular, within the domains of biofuels, bioproducts, and biomaterials, there remains a significant disconnect between low TRL research and the development of scalable, economically viable, and regulation-compliant industrial applications.

From an industry standpoint, one of the most pressing issues is the difficulty in converting academic, thesis-based, and laboratory-scale research outputs—often developed at low TRLs—into high-TRL, "ready-for-practice" solutions that are competitive in the marketplace.

These early-stage innovations frequently lack the technical maturity, economic justification, and certification required to meet real-world industry standards, market demand, and legal frameworks.

For this reason, 3R-BioPhosphate Ltd identifies the scale-up of technologies and integrated process demonstrations at higher TRLs as a top priority for joint academia-industry collaboration. Such efforts must be grounded in practical considerations, including economic feasibility, supply chain integration, user-oriented product development, and conformity with strict regulatory and certification requirements. However, there are several persistent barriers to effective collaboration. These include the lack of harmonized datasets, incompatible research and operational methodologies between academia and industry, and complex regulatory environments that slow down the innovation pipeline. Bridging these gaps will require coordinated, multidisciplinary efforts and a shift towards co-designed research agendas where industrial needs are considered from the outset.

By focusing collaborative efforts on delivering high-TRL, market-competitive biorefinery technologies, academia and industry can jointly accelerate the deployment of sustainable and economically robust solutions. The key is converting low TRL research results into “ready for practice” market competitive high TRL scale-up demonstrations. In addition, the thesis and laboratory-based low TRL research results are not compatible and applicable for scale-up up aiming for “ready for practice” market competitive high TRL solutions with economical, user demand-driven driven and Authority-certified lawful products.

8. Chemical recycling converts post-consumer plastics into usable intermediates

Chemical recycling converts post-consumer plastics into usable intermediates (monomers, naphtha-like streams, waxes/oils) through thermolysis (medium/high-T pyrolysis, catalytic variants), solvolysis/depolymerization (e.g., PET→BHET/DMT, PS→styrene, PC→BPA derivatives), and hydrothermal routes (HTL for wet feeds). In a biorefinery context, these streams may be co-processed with biomass-derived oils (e.g., HTL biocrudes or pyrolysis oils), enabling shared upgrading assets, hydrogen management, and carbon circularity.

Key integration constraints are additives/legacy contaminants (halogens, N/O-bearing inks/adhesives, metals, particulate), specification alignment with refinery/petrochemical hosts, and robust analytics (total/organic halogens, N/O speciation, trace metals, stability). The intent is evidence-based and non-prescriptive: many mitigations are proven at lab/pilot scale, while site validation remains essential.

Main scientific/technological gaps (chemical recycling & plastic/biomass blends):

- Contaminant fate & specs: limited, non-harmonized datasets on halogen carryover (Cl/Br/F) into oils, N/O markers from EVOH/PA/inks, and metals/particles; sparse round-robin analytics and acceptance criteria across hosts.
- Upgrading reliability: insufficient long-run validation of hydrotreating/hydro processing for mixed plastic–biogenic oils (catalyst tolerance to organ halogens, phenolics, TAN, nitrogenates; fouling control).
- PVC/fluoropolymer management: need scalable pre-/in-process dehalogenation and HF-safe scrubbing/metallurgy; guidance for segregation and waste handling.
- Process integration: Recommended practices for split-route operations (e.g., PET/PS depolymerization; PO thermolysis) compared to single-train thermal processes, with consideration of mass balance, product quality, and economic implications.
- Data & models: lack of predictive correlations linking feed composition → oil quality → upgrading severity; limited digital twins and datasets for ML.
- Sustainability evidence: gaps in LCA/TEA for co-processing with biomass, including mass-balance recycled-content accounting and allocation rules.

Most urgent areas for joint academia–industry efforts:

- Analytical harmonization: inter-lab methods for total/organic halogens, N/O speciation (GC×GC–HRMS), metals/particles, and stability; creation of certified reference oils.
- Upgrading trials at host sites: controlled hydrotreating/co-processing campaigns on representative oils (plastic-only and plastic+biomass), with catalyst life and fouling KPIs.
- Halogen management toolkits: scalable pre-sorting, dechlorination/debromination, acid-gas scrubbing (HCl/HBr/HF), and material selection guidelines.
- Integration playbooks: decision trees for split vs combined routes, routing of heavies, and spec-driven blending.
- Open data (pre-competitive): minimal, anonymized oil-quality matrices plus unit outcomes to enable predictive models.

The current barriers to improve and create collaboration in the plastic recycling are:

- Data sensitivity/IP (oil quality, catalysts, yields), non-aligned specifications, fragmented terminology.
- Regulatory ambiguity (definitions, recycled-content mass balance, Food Contact Material/REACH interfaces).
- Infrastructure risk (HF/halogens metallurgy), lack of long-duration pilots, and limited standard test protocols.

Suggestions by area:

- Chemistry/ChemEng: halogen/N/O removal sequences; short hot-vapor residence to limit PAH; selective cracking vs hydrogen-demand minimization; fouling/solids control.
- Engineering/Automation: inline halogen monitors; particle counting; corrosion probes; digital twins fed by standardized QC.
- Environmental/Circularity: harmonized LCA/TEA with co-processing rules; exergy and material circularity indicators; fate of scrubbing/adsorbent wastes.
- Economics/Policy: clear acceptance specs; recycled-content accounting; incentives for pilot co-processing and pre-competitive datasets.

CONCLUSIONS

The transition toward a sustainable, low-carbon, and circular bioeconomy makes necessary the effective valorization of waste biomass into high-value bio-based products. The primary objective is to promote the development of biorefinery applications mostly related to the sharing of results and data reliable from different process in order to create and integration of them.
These applications encompass the conversion of biomass, including agricultural by-products, food waste, digestate, and forestry residues, into functional materials, sustainable energy carriers, and high-performance products for both industry and the environment.
The current approach of biorefinery integrates material science, process optimization, LCA, and stakeholder engagement to address the discrepancy between laboratory innovation and market adoption. Collaborations with small- and medium-sized enterprises (SMEs), research centers, and industrial users facilitate the validation of bio-based solutions in real-world settings, thereby informing strategic pathways for their implementation.

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